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Statistical analysis of environmental consequences of hazardous liquid pipeline accidents

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Abstract

Although pipelines are the safest method to transport fuels, they are associated with risks due to failures, leading to significant negative consequences. This paper investigates pipeline accident data provided by PHMSA (Pipeline and Hazardous Material Safety Administration) between 2010 and 2017, with a focus on environmental consequences of hazardous liquid pipeline accidents. The average amount of released product, the average time elapsed between the accident, the emergency response from the oil company, and the average costs of environmental remediation are estimated. The impact on soil, water, and wildlife is investigated for frequency and magnitude, where possible. It was found that, on average, 85% of product released after an accident remained unrecovered, 53% of accidents led to soil contamination, 41% of accidents impacted environmentally sensitive areas, and 92% of water crossing pipelines involved in accidents were uncased. From an annual average total cost of USD 326 million, annual average environmental damage and remediation costs were USD 140 million. This analysis assists in the diagnosis of challenges that might be addressed with improved maintenance and inspection programs, especially for pipelines at higher risk of negative environmental consequences. Finally, the performance of safety management systems should be improved to efficiently respond to emergencies.

Keywords: Petroleum engineering, Environmental science

1. Introduction

Pipelines play an important role in providing fuels for transportation and residential, commercial, and industrial uses [1]. However, although pipelines are the safest and most economical method to transport fuels [2, 3], they are associated with risks due to failures that can lead to significant negative environmental consequences. In the case of a spill, the released product becomes a hazard by dispersing in the environment, contaminating water bodies, soil, and potentially affecting people and wildlife.

On November 16, 2017 TransCanada shut down the Keystone pipeline after a drop in pressure was identified on a section of a pipeline in Amherst, South Dakota. By the time the spill was detected, 5,000 barrels of oil was released to the surrounding environment [4]. Emergency management, engineering, environmental management, and safety specialists have been evaluating the consequences of the accident since its occurrence. In March 2013, a pipeline located in Mayflower, Arkansas, ruptured causing part of the 3,190 barrels of crude oil to reach a suburban area, and causing water and soil contamination, and adverse effects on wildlife [5]. The oil flowed into Lake Conway, twenty-one houses were evacuated and wetland vegetation, waterfowl and various animal species were impacted [6]. A Corrective Action Order (CAO) was issued by the Pipeline and Hazardous Material Safety Administration (PHMSA) to the oil company responsible for the accident, ExxonMobil. In the report, PHMSA ordered ExxonMobil to revise pipeline safety measures to help prevent future accidents, improve training to its spill first responders, and equip strategically chosen sites along the pipeline with emergency supplies [6].

Although pipelines in the US have recent failure rates on the order of 10^{-3} and 10^{-4} accidents per km per year for onshore and offshore pipelines, respectively, which are the lowest failure rates among methods of transporting fuels [2, 3, 7], the impact of a single accident on the receiving environment and communities can be large. Moreover, oil pipeline accidents can have a large impact on oil companies in terms of costs [8], as they are responsible for the expenses related to the accident. Environmental Risk Assessment (ERA), State of Environment Reporting (SOE), Environmental Impact Assessment (EIA), and risk management are some of the methods to identify, analyze, and present information about environmental risk with the purpose of informing the planning and decision-making processes [9]. The assessment and reporting of environmental consequences from previous failures can be used to identify risk reduction strategies, revise emergency management and response plans, and develop integrity management programs for existing pipelines and pipeline designs under development.

The International Energy Outlook [10] estimated a worldwide increasing energy consumption from 90 million barrels per day in 2012 to 121 million barrels per day in 2040. While governments, researchers, and experts develop the infrastructures for renewable energy, this growth of 34% of global energy demand needs to be satisfied. In Canada, the hazardous liquid pipeline network transports approximately 4 million b/d of oil and oil products and by 2030 it will increase to more than 5.5 million b/d [11]. Therefore, the capacity of the hazardous liquid pipeline network in Canada is projected to grow 39% by 2030. The transportation of fuels via pipelines is the safest method to move oil from drilling locations to customers [2, 3] and, to meet the growing demand for fossil fuels new pipeline projects have recently been approved in Canada and the United States (US): the Keystone XL, the Trans Mountain Expansion, and the Towerbirch Expansion Project are planned to start construction in 2018 [12] and the Corpus Christi Crude Oil Terminal and the Platte Twin (Guernsey to Patoka) are two of several projects planned to be added by 2021 [13, 14]. This growth in the pipeline system highlights the importance of monitoring and analyzing the state of the pipeline network, and the risks associated with it.

Past accident data are used in this paper to investigate the impact that hazardous liquid pipeline accidents have on the environment in terms of contamination and on the oil companies in terms of the costs of environmental remediation. New pipeline design and existing pipeline risk management programs can benefit from quantitative analyses such as the one presented in this paper, because it provides an up to date statistical analysis of the frequency and magnitude of water and soil contamination and adverse effects on wildlife, including details on the type of water contaminated and types of wildlife affected. Moreover, no previous studies exist that present a quantitative analysis of environmental consequences of hazardous liquid pipeline failures. Sensitive environmental receptors are a particular focus, including the frequency of failures in hazardous liquid pipelines that cross water bodies or High Consequence Areas (HCAs, as defined by PHMSA), which include ecologically sensitive areas. Moreover, the time elapsed between the accident and its identification, and the time elapsed between the identification and the initiation of remediation is investigated to assess the relation to the volume of product released. The average annual costs associated with hazardous liquid pipeline accidents are shown along with the costs of environmental remediation. An overview of the annual mileage and failure rates from 2010 and 2016 is also provided. The results of these analyses will help the industry and emergency management agencies and societies to improve emergency preparedness and response where lacking efficiency and/or effectiveness and inform the public of the frequency and impact of environmental consequences and related risks associated with hazardous liquid pipelines.

2. Methods

2.1. Data source

Information about oil and gas pipeline accidents in the United States is collected by the Pipeline and Hazardous Material Safety Administration (PHMSA) of the US Department of Transportation (DOT). Similarly, the National Energy Board (NEB) collects information about oil and gas pipeline accidents in Canada. PHMSA and NEB differ significantly in their jurisdiction, accident reporting criteria, and quality and quantity of information provided [15]: PHMSA regulates 76% of inter- and intra-state pipelines in the US, while the NEB regulates the 9% of oil and gas pipelines in Canada that are inter-provincial. There is insufficient information provided by the NEB to quantify and evaluate environmental consequences of hazardous liquid pipeline accidents. Thus, the NEB does not provide adequate information to assess the environmental impact of hazardous liquid pipelines and, for this reason, this study considers data provided by PHMSA, which is publicly accessible online [16]. Although PHMSA has collected and made available information about hazardous liquid pipelines since 1986, the data available are temporally inconsistent in terms of reporting criteria. The definition of an “accident” has changed over time and, for this reason, several pre-2010 accidents were not included in the dataset because they did not meet the reporting criteria. PHMSA increased the quality and quantity of information provided and more details are provided. This study focuses on information provided by PHMSA between 2010 and 2017 because it is collected within the same requirements and reporting criteria, which allows for a more thorough analysis of hazardous liquid pipeline failures in the U.S.

This study considers both offshore and onshore gathering and transmission hazardous liquid pipelines regulated by PHMSA. Information on environmental consequences resulting from pipeline accidents are collected by PHMSA in 21 descriptive database fields, including wildlife impact (i.e. fish, birds, terrestrials), soil contamination and remediation, and water contamination (i.e. surface water, groundwater, drinking water, public water). However, the database reports information in the form of a “Yes/No” statement and details regarding the number and species of animals impacted, the volume of soil contaminated, and the concentration of chemicals and contaminants are missing. Therefore, because there is no data available to quantify the degree of severity (i.e. area affected by the spill or number of animals involved), it is only possible to evaluate the consequences on wildlife, water, and soil due to pipeline failures by considering the frequency with which they are impacted.

The Code of Federal Regulations (49 CFR Parts 101, 195) [17] requires oil pipeline operators to submit accident reports to PHMSA within 30 days of an accident. These reports contain information on the pipeline, accident prevention actions, and post-

accident response that can be used for inspection planning and risk assessment. The database provided by PHMSA, which contains information on hazardous liquid pipeline accidents that occurred between 2010 and 2017, is suitable to analyze and quantify the frequency with which hazardous liquid pipeline accidents impact the environment. However, information about environmental consequences is missing from some of the categories between 2010 and 2014. The data quality assessment conducted by PHMSA in 2009 [18] shows that the pre-2010 accident datasets are missing 60–90% of data, and 54% of PHMSA personnel agreed that the information contained in the database was inaccurate for decision-making purposes. PHMSA used a strategic plan to reduce missing information and produce a more accurate database by including more accident-related details. Moreover, the US government has proposed extending the regulations to all gathering pipelines because only 10% of gathering pipelines in the US are currently regulated by PHMSA [19, 20].

Title 49 CFR § 195.50 [17] defines the criteria for an accident to be reported to PHMSA. An accident report is required if a release of hazardous liquid results in:

- Explosion or fire not intentionally set by the operator;
- Release of 5 gallons (19 liters) or more of hazardous liquid;
- Death of any person;
- Injury necessitating hospitalization;
- Estimated property damage, including cost of clean-up and recovery, value of lost product, and damage to the property of the operator or others, or both, exceeding USD 50,000.

This paper focuses on the information provided by PHMSA that describes the conditions and magnitude of environmentally-related consequences: the volume of released product in an accident, pipelines crossing water bodies, soil and water contamination, impact on wildlife, pipelines crossing High Consequence Areas (HCA), time elapsed between an accident and its identification, time elapsed between the identification of an accident and the initiation of remediation, and costs associated with environmental remediation.

The product released in an accident can be divided into unintentional and intentional releases. Product is released unintentionally due to accidental and uncontrolled spills, while product is released intentionally due to controlled spills that result from maintenance, pressure control, or functionality tests. Intentional releases are usually supervised and managed such that product can be recovered, while unintentional release represents the major consequence that most often leads to environmental harm and cost increases.

PHMSA requires oil and gas operators to take additional precautions for water-crossing pipelines, as they are subject to higher risks (i.e. highly corrosive sea water, shear stress from water flow) and potentially lead to large consequences for the environment. For example, Title 49 CFR § 195.412 (b) requires operators to inspect each onshore crossing under a navigable waterway to determine the condition of the crossing at intervals not exceeding 5 years. Pipelines that cross drinking water sources are considered to occur in an HCA and they are subject to more restrictive regulations for integrity management (49 CFR § 195.452). A standard practice of oil and gas operators is to use alternative materials or cased pipelines in water-crossing locations. HCAs identify specific locations defined as sites where a product release might have the most significant adverse consequences. Oil and gas pipeline companies must devote additional focus, efforts, and analysis to operate and ensure the integrity of pipelines located in HCAs. For hazardous liquid pipelines, the HCA designation focuses on:

- High population areas (i.e. “urbanized areas” and “designated place” as defined by the U.S. Census Bureau);
- Drinking water sources, which include water sources supplied by surface water and/or wells and areas where secondary (i.e. alternative) water sources are not available, and land areas in which hazardous liquid spills could affect the water supply;
- Unusually sensitive ecological areas, where critically imperiled species, multiple examples of federally listed threatened and endangered species, and migratory water birds are found.

Oil and gas pipeline operators must identify the segments of the pipelines that could affect HCAs in case of accidents, with the assumption that a release can occur at any point, even if the probability of having a spill is relatively low.

The total cost of an accident is the sum of the estimated costs of public and non-operator private property damage paid or reimbursed by the operator, loss of product released unintentionally and during intentional and controlled blowdown, operator’s property damage and repairs, emergency response, and environmental remediation. This study estimates the cost of environmental remediation as a percentage of the total cost of an accident.

Supporting details regarding PHMSA’s hazardous liquid scope, definitions, reporting criteria and other general information can be found on Title 49, Subtitle B, Chapter 1 (Subchapter D), Part 195 of the Code of Federal Regulations.

2.2. Estimation of failure and environmental impact rates

A pipeline's failure rate is calculated by dividing the number of failures by the overall length of the pipeline, as per the following formula:

$$f_{rate_i} = \frac{n_{tot_i}}{l_{tot_i}} \quad i = 2010, \dots, 2017$$

where, f_{rate} is the failure rate, n_{tot} is the total number of failures, l_{tot} is the overall length, and i is the year. The same approach is adopted to calculate the rates of water and soil contamination, wildlife and wildlife types affected, and contaminated HCAs:

$$EI_{rate_i} = \frac{n_{tot_i}}{l_{tot_i}} \quad i = 2010, \dots, 2017$$

where EI is the environmental impact type (i.e. soil contamination), n_{tot} is the total number of accidents that led to environmental consequences (i.e. soil contamination), l_{tot} is the overall length of the pipeline network, and i is the year.

The failure and environmental impact rate is calculated for each year between 2010 and 2017 based on the total length of all regulated pipelines. The 2017 mileage is not yet available from PHMSA and, for this reason, the 2016 mileage is used to calculate the failure rate for 2017 as it is not likely that there is a significant increase in hazardous liquid pipeline length between 2016 and 2017 based on year-over-year increases [7]. For the same reason, the rates of water contamination, soil contamination, wildlife affected, wildlife types affected, and HCAs contamination for 2017 are calculated using the 2016 mileage data. In this study, the confidence interval for the population mean is equal to 80% (z-value = 1.28).

2.3. Regression analysis

The sum of the time elapsed between the accident and its identification and the time elapsed between the identification and the initiation of remediation is investigated along with the unintentional and intentional volume released in an accident to determine if there is a relationship between total time elapsed and volume released. A linear regression analysis is used, although there is evidence of skewness in both the released volume and time elapsed data. In order to avoid violating the assumptions of linear regression analysis, a data log-transformation was necessary to reduce data skewness and obtain normally distributed data [21, 22]. For linear models, data transformation is important to reduce the model error terms closer to a normal distribution, improve homogeneity of variances, reduce the influence of outliers, improve linearity, and reduce the impact of interaction effects [23, 24, 25]. In this paper, the linear regression analysis that investigates the relationship between time elapsed and volume released considers accidents with elapsed time equal or greater

than 1 minute (49% of all data), because they represent a delay in identification or company response.

Although both dependent variables were not normally distributed, log-transformation allowed to normalize data and perform the linear regression analysis. By log-transforming data, the skewness was reduced by 95.3% (from 10.86 to 0.51) for the dependent variable indicating the total volume released and by 95.27% (from 22 to 1.04) for the independent variable that describes the total time elapsed between the accident and the initiation of remediation. While the normal probability plot of the non-transformed data shows an exponential trend, indicating a strong skewness, the normal probability plot of the log-transformed data shows a straight line, indicating a normal distribution.

3. Results

The hazardous liquid pipeline network has grown from 292,879 km in 2010 to 342,204 km in 2016, as shown in Fig. 1, which is an increase of about 14% (49,325 km) over the 7 years. The rate of accidents reported in Fig. 2 exhibits a local peak in 2014 of 1.41×10^{-3} followed by decreases in 2015 and 2016. Table 1 summarizes the annual mileage, the annual number of accidents, and the annual failure rates. Fig. 2 indicates that there was no discernable trend in either the annual ratio or the total amount of unintentional, intentional, and recovered product releases. The highest annual average volume released between 2010 and 2017 was 1,394 barrels in 2013. The peak observed in 2013 was due to 4 large hazardous liquid releases: 20,600 barrels of crude oil were released in North Dakota, 18,400 barrels of ethane/propane mix were released in Illinois, 11,405 barrels of liquefied petroleum gas in West Virginia, and 23,702 barrels of the same product in Louisiana. On average, 85.2% ($\pm 30\%$) of released product remained unrecovered after an accident. Although the data about accidents for 2017 extends only to October and does not encompass the full year, it is possible to note that the values of unintentional plus

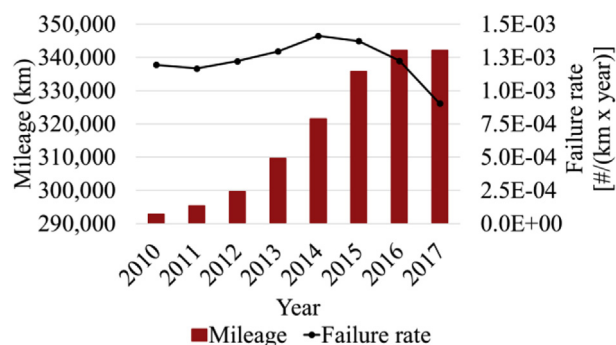


Fig. 1. Annual hazardous liquid pipeline mileage and failure rate for hazardous liquid pipelines.

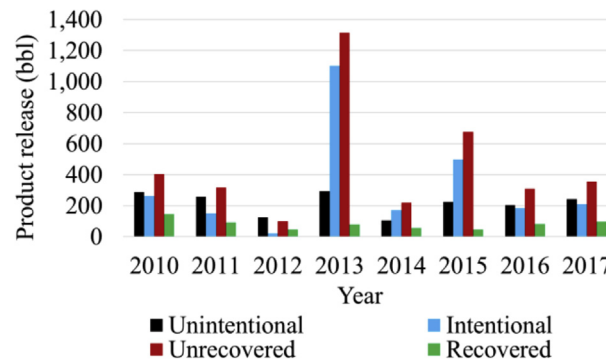


Fig. 2. Annual average unintentional, intentional, recovered, and unrecovered product released in hazardous liquid pipeline accidents.

Table 1. Annual mileage, number of accidents, and failure rates for hazardous liquid pipeline accidents.

Year	Mileage	Number of accidents	Failure rate
2010	292,878.56	350	1.20E-03
2011	295,443.53	345	1.17E-03
2012	299,694.13	366	1.22E-03
2013	309,657.10	401	1.29E-03
2014	321,535.66	454	1.41E-03
2015	335,894.07	461	1.37E-03
2016	342,203.50	419	1.22E-03
2017	342,203.50	309	9.03E-04
Average	317,438.76	388.12	1.22E-03

intentional and recovered release are higher for 2017 than 2011, 2012, 2014, and 2016.

Fig. 3 shows that since 2010, an annual average of 0.8% of accidents occurred on water crossing pipelines. Of this 0.8%, 91.8% ($\pm 30.5\%$) of pipelines were uncased. The annual average volume of product released into water bodies was 234.7 barrels (± 53 barrels) (Fig. 4). Oceans are categorized separately from fresh water bodies (designated as “water” by PHMSA), which include surface, groundwater, drinking, private well, and public water. The largest spill on water crossing pipelines occurred in 2010 near Marshall in Michigan, also known as the Kalamazoo River spill, as 8,033 barrels of crude oil were released into Talmadge Creek and the Kalamazoo River. In 2014, 8,000 barrels of gasoline contaminated surface and groundwater near Belton, South Carolina. In 2016, the Colonial Pipeline in Shelby County, Alabama, leaked 7,370 barrels of gasoline, of which 2,111 were recovered. A partial shutdown of the pipeline was required, causing gas shortages in many of the southeastern United States, and Alabama, Tennessee, Georgia and Virginia declared states

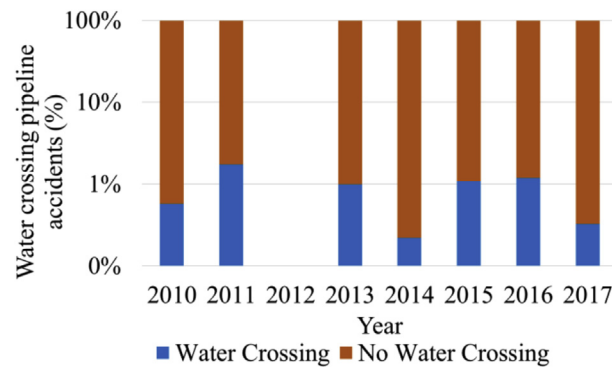


Fig. 3. Annual ratio of hazardous liquid pipeline accidents occurred on water crossing pipelines.

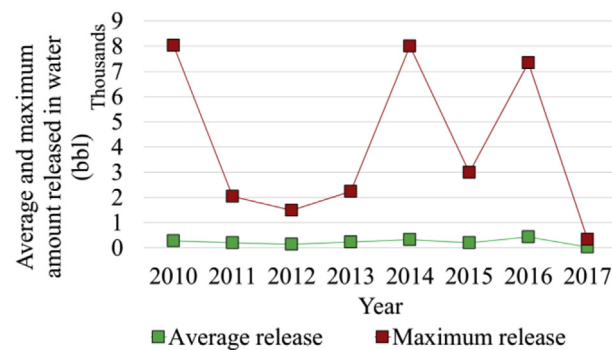


Fig. 4. Annual average and total volume released in water bodies due to hazardous liquid pipeline accidents.

of emergency. Almost 30% of the time, the volume released into water bodies was above 50 barrels. The annual average water contamination rate was 1.07×10^{-4} accidents per km per year and the annual average ocean contamination rate was 1.03×10^{-5} accidents per km per year (Fig. 5). Table 2 reports the annual values of water contamination rates: the highest frequency of water contamination is 1.47×10^{-4} accidents per km per year in 2010. 8.7% ($\pm 2\%$) of the pipeline accidents that occurred between 2010 and 2017 led to water contamination. Fig. 6 shows that

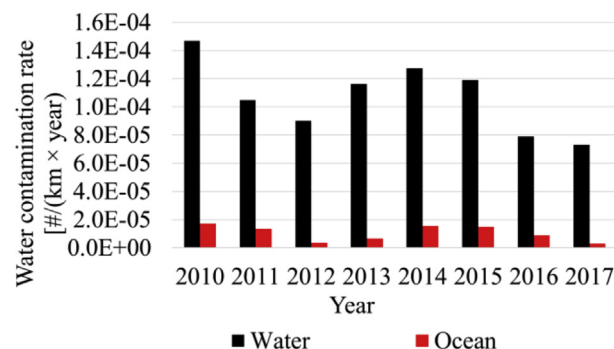


Fig. 5. Annual water contamination rate due to hazardous liquid pipeline accidents.

Table 2. Annual water and soil contamination, wildlife adverse effect, and failure rates [#/ (km × year)].

Year	Hazardous liquid pipeline failure			Water contamination			Soil contamination			Adverse effects on wildlife		
	Upper limit	Average	Lower limit	Upper limit	Average	Lower limit	Upper limit	Average	Lower limit	Upper limit	Average	Lower limit
2010	1.26E-03	1.20E-03	1.13E-03	1.58E-04	1.47E-04	1.36E-04	6.08E-04	5.36E-04	4.64E-04	3.47E-05	3.07E-05	2.68E-05
2011	1.23E-03	1.17E-03	1.10E-03	1.16E-04	1.05E-04	9.42E-05	5.33E-04	4.60E-04	3.88E-04	2.09E-05	1.69E-05	1.30E-05
2012	1.29E-03	1.22E-03	1.16E-03	1.01E-04	9.01E-05	7.94E-05	5.73E-04	5.01E-04	4.28E-04	1.06E-05	6.67E-06	2.74E-06
2013	1.36E-03	1.29E-03	1.23E-03	1.27E-04	1.16E-04	1.06E-04	6.44E-04	5.72E-04	4.99E-04	3.62E-05	3.23E-05	2.84E-05
2014	1.48E-03	1.41E-03	1.35E-03	1.38E-04	1.28E-04	1.17E-04	8.13E-04	7.40E-04	6.68E-04	1.95E-05	1.56E-05	1.16E-05
2015	1.44E-03	1.37E-03	1.31E-03	1.30E-04	1.19E-04	1.08E-04	1.02E-03	9.44E-04	8.71E-04	1.88E-05	1.49E-05	1.10E-05
2016	1.29E-03	1.22E-03	1.16E-03	8.96E-05	7.89E-05	6.82E-05	8.97E-04	8.24E-04	7.52E-04	3.02E-05	2.63E-05	2.24E-05
2017	9.69E-04	9.03E-04	8.37E-04	8.38E-05	7.31E-05	6.24E-05	6.69E-04	5.96E-04	5.24E-04	1.56E-05	1.17E-05	7.75E-06
Average	1.29E-03	1.22E-03	1.16E-03	1.18E-04	1.07E-04	9.64E-05	7.19E-04	6.47E-04	5.74E-04	2.33E-05	1.94E-05	1.54E-05
Contamination rate to total failure rate (%)				11%	9%	7%	59%	53%	47%	2%	2%	2%

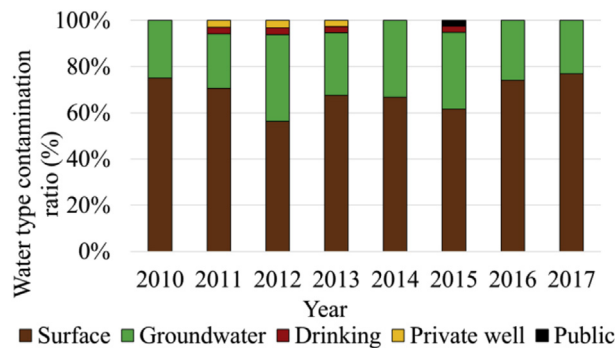


Fig. 6. Annual ratio of water type contamination due to hazardous liquid pipeline accidents.

surface water was the most often contaminated water type (68%), followed by groundwater (29%), drinking water and private well water (1%), and public water (<1%).

The PHMSA database reports no missing information for water contamination; however, information about soil contamination is often missing for the years 2010 through 2014. On average, 53% ($\pm 6\%$) of accidents lead to soil contamination. The details of impacts related to soil contamination (e.g. volume or area of contaminated soil) are not recorded in the database provided by PHMSA and, for this reason, it is not possible to evaluate the magnitude of the environmental impact on soil due to hazardous liquid pipeline failures. Fig. 7 shows that the average soil contamination rate over the period 2010–2017 was 6.47×10^{-4} (as also indicated in Table 2), while the average soil remediation rate was 3.5×10^{-4} . Moreover, on average, 54% of accidents reported soil remediation after soil contamination. The soil contamination rate could be underestimated due to missing data between 2010 and 2014. The majority of missing information between 2010 and 2014 appears to have been attributed to “No soil remediation” in 2015, 2016, and 2017, as the ratio of soil remediation stays steady over the time window. This suggests that the 56% of

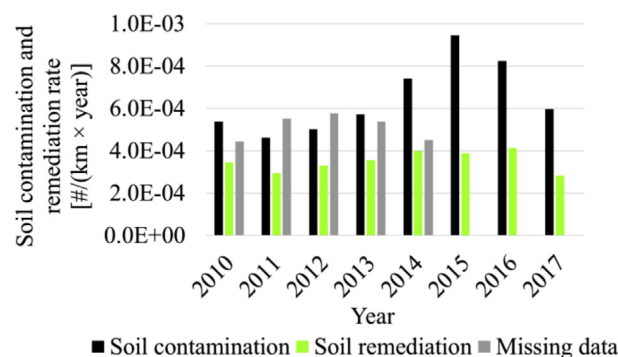


Fig. 7. Annual soil contamination, soil remediation, and missing data rates for hazardous liquid pipeline accidents.

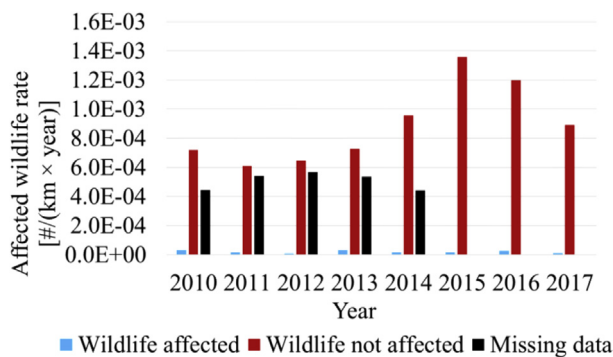


Fig. 8. Annual rates of adverse effects on wildlife due to hazardous liquid pipeline accidents.

accidents where no remediation occurred could be an underestimate, although the data are unclear in this regard.

Pipeline accidents often have an impact on the wildlife located in the surrounding areas that can lead to mortality or to sublethal effects on individuals. Information regarding adverse effects on wildlife was often missing between 2010 and 2014 in the PHMSA database (Fig. 8). Table 2 reports the annual values of the frequency with which wildlife was affected. The average over the period 2010–2017 of adverse effects on wildlife after a spill is 1.94×10^{-5} accidents per km per year, which is 2% ($\pm 3.2 \times 10^{-3}$ %) of all accidents. The PHMSA data also includes the types of wildlife affected as a result of an accident. On average, 39% of accidents had adverse effects on fish, 33% on birds, and 28% on terrestrial wildlife. It is not possible to calculate the magnitude of the impact on wildlife because PHMSA provides data only about the occurrence of the adverse effect on wildlife (i.e. yes/no wildlife affected) and no information on the number of animals involved or the severity of impacts (e.g., lethal or sub-lethal effects) is provided.

The annual frequency with which hazardous liquid pipeline accidents impacted HCAs registered a peak in 2014 and a decrease starting in 2015. The average over the period 2010–2017 is 5.04×10^{-4} accidents per km per year, or 41% ($\pm 3\%$) of the time.

It is possible that the time elapsed between the occurrence and identification of an accident, plus the time elapsed between accident identification and the initiation of remediation, is related to the volume released. The sum of these two variables were investigated along with the volume released to determine whether there is a correlation between the amount of product released and the total time taken to respond to an accident. Fig. 9 shows the results of the regression analysis; decreasing the detection and initiation of remediation time is correlated with a decrease in the volume of product released. Although results do not present a strong coefficient of determination ($r^2 = 0.036$, $n = 1520$), due to the dispersion of the data points, the

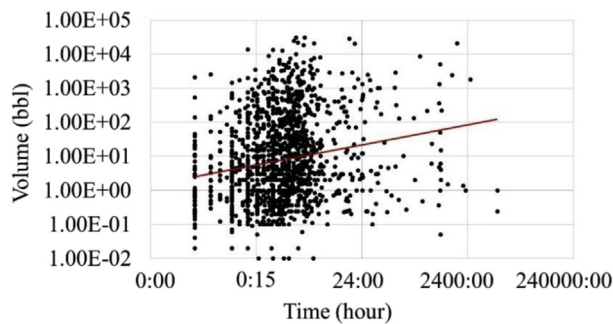


Fig. 9. Linear regression analysis between time elapsed and released volume in hazardous liquid pipeline accidents.

p-values of the intercept and the independent variables indicate a statistically significant regression model (1.7×10^{-82} and 1.4×10^{-13} , respectively).

The annual average time elapsed between an accident and its identification is 9 hours, while the annual average time elapsed between accident identification and operator's response is 5 hours and 13 minutes (Fig. 10). Although the data do not cover the complete year, the values for 2017 for the elapsed time between an accident and its identification are larger than for 2014 and 2016. In addition, results for 2010, 2011, 2012, and 2013 contain bias due to missing information in the PHMSA database. 73% ($\pm 5\%$) of hazardous liquid pipeline accidents over the period 2010–2017 were identified without delay, meaning that the time between the occurrence of an accident and its identification is zero, and 8% ($\pm 4\%$) had an unknown elapsed time to response.

PHMSA gathers information about total costs associated with hazardous liquid pipeline accidents. The total costs are divided into various types: Fig. 11 shows that, on average, from an annual total cost of USD 326 million (\pm USD 150 million), environmental damage and remediation cost hazardous liquid pipeline operators USD 140 million per year. The peak observed in 2010 is due to the Kalamazoo river spill,

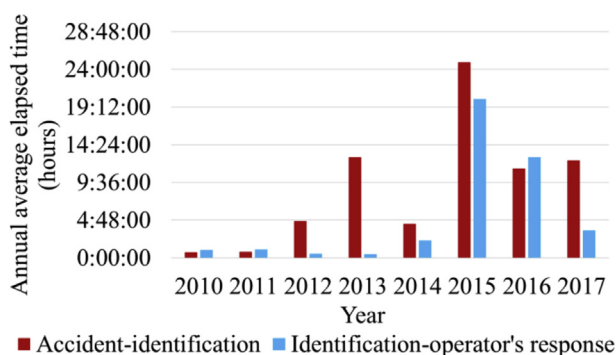


Fig. 10. Annual average of time elapsed between an accident and its identification and accident identification and initiation of remediation.

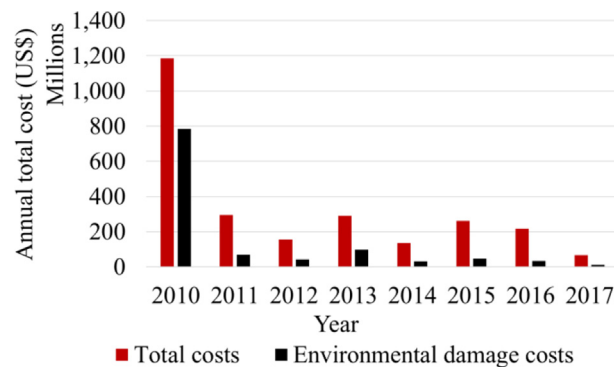


Fig. 11. Annual total environmental damage costs due to hazardous liquid pipeline accidents.

which resulted in the highest total and environmental damage costs from pipeline spills recorded between 2010 and 2017. On average, 28% ($\pm 7\%$) of the total costs of accidents are due to environmental damage and remediation.

4. Discussion and conclusion

Although the hazardous liquid pipeline network has grown by 14% between 2010 and 2016, the failure rate does not show a similar trend, indicating a decrease after a peak in 2014. Most of the associated product releases during the period of study were smaller than 50 barrels, however accidents that involve large volumes of released product lead to larger consequences in terms of environmental damage and costs associated with the accident. This trend was variable according to the commodity type, the location of accidents, the type of environment, and other circumstances that differ from accident to accident. The Kalamazoo River spill in 2010 caused crude oil to spread to a Michigan wetland; water and soil contamination and adverse effects on wildlife were recorded. The accident occurred in an environmentally sensitive area with low human population and the product spread rapidly. This accident cost Enbridge Energy nearly USD 1 billion and, despite the oil company's extensive environmental remediation work, residual environmental impacts persist [26].

A large portion of the volume released to the environment as a result of pipeline failures and releases often remains unrecovered and dispersed in the environment. Additional actions should be taken to reduce the amount of unrecovered product and increase soil remediation rates. The PHMSA database did not include reasons for not remediating soil after a spill or for failing to more effectively recover the released product. By containing the dispersion of the material in the environment or improving spill detection systems, it is possible to reduce environmental damage and related costs. For example, ENI (Ente Nazionale Idrocarburi S.p.A.) aimed at reducing oil spills by focusing on technical preventative aspects, control, and

quality/preparedness of intervention and participation in research projects (i.e. e-VPMS - Eni Vibroacous Pipeline Monitoring System-, which started as a research project and became a patented product to detect vibrations from ground excavations, which aids in preventing the collision between excavation machineries and existing pipelines) [27]. Through this policy, ENI managed to reduce the number of oil spills and to recover almost the total volume spilled at the site of accidents.

The volume released in accidents that occurred in 2013 was larger than in 2010, although the related costs are larger in 2010 than 2013. This indicates that there is not a direct relationship between the amount released and related costs of accidents, because the accident costs reflect the variability of the circumstances and conditions of each accident. For example, 2014 had the highest failure rate, contaminated HCAs rate, the largest total product released in water, and some of the highest water and soil contamination rates, although the total costs and related environmental remediation cost in 2014 are among the lowest in the study period. In contrast, 2013, which had the second highest total costs and environmental remediation costs, also had the second highest average time to identify an accident, and the largest total product released and unrecovered. 2015 shows a similar relationship by recording the highest average time elapsed to identify an accident and the second largest total product released and unrecovered. These results lead to the conclusion that by reducing the identification time in case of an accident, the released product could be more likely recovered and decrease, by consequence, total and related environmental costs, independently of the number of accidents and failure rate.

Results show that an average of approximately 9% of accidents led to water contamination between 2010 and 2017. Accidents on water crossing pipelines are generally rare, and cased water crossing pipelines are less frequently involved. There is no indication in the PHMSA database whether or not uncased water crossing pipelines are built using alternatives to casing. It follows that casing water crossing pipelines seems to enhance pipeline safety and could be adopted in future designs as a hazard deterrent. By casing water crossing pipelines, in the case of a release, the product in the pipeline can be better contained and consequently environmental impacts minimized, especially in a highly dispersive environment like water.

Information on soil contamination and remediation and adverse effects on wildlife is partially missing between 2010 and 2014. After 2014, the annual rates of contaminated soil with no remediation increased, while the rates of remediated soil remained steady: it appears that most of the missing values between 2010 and 2014 were replaced after 2014 by accidents reporting no soil remediation. Similarly, missing information between 2010 and 2014 regarding affected wildlife seem to have been replaced by accidents reporting no effects on wildlife between 2015 and 2017. Generally, soil is the most frequently affected type of environmental medium, reporting the largest average contamination rate, followed by water contamination and

adverse effects on wildlife. Among the types of wildlife, fish were affected in 11% more instances than birds and terrestrials. This means that in the case of an accident, pipelines located in or close to water bodies should be better isolated to keep the released product from coming into contact with or widely dispersing in water. Several methods can be adopted to lower the risk of impacting fish, including reducing the operating pressure and the nominal diameter of those pipelines located close to water bodies or placing valves to minimize the released quantity. The contamination of water affects fish over other species; however, gathering information about the type of birds (i.e. water or terrestrial) and terrestrials affected (i.e. flying insects, soil invertebrates, ungulates) would help to better understand the nature and magnitude of the consequences on the environment after a spill, especially for accidents that occur close to or in HCAs.

The regression analysis relating the total time elapsed to the volume of product released showed statistically significant results, indicating that by delaying the accident identification and, consequently, the accident remediation the volume spilled increases to some degree. However, the coefficient of determination is descriptive of the cloud-shaped data points; the dispersion of the data points could be due to other conditions not considered as part of the regression, including the different release modes related to the accident cause. For example, leaks would imply a slow release of material that can be detected immediately by supervisory control and data acquisition (SCADA) systems or a drop in pressure for high pressure pipelines. However, the Kalamazoo River spill continued for 17 hours before being detected, showing that the technologies for accident detection are subject to failure. Moreover, mechanical punctures caused by third party damage can be detected and addressed immediately, but they can cause a large amount of material to be dispersed in a short period of time, depending on the size of the fracture. In this way, the variability of the dynamic of the accident also influences the resulting volumes released, a factor which was not considered in the regression between the total time elapsed and the volume released.

Finally, this study found that the cost of environmental damage and remediation due to hazardous liquid pipeline accidents is, on average, almost one third of the total costs of pipeline failures. This cost can be reduced by enhancing pipeline safety and reducing the risk of pipeline failures. Additional details about the types of receiving environment affected by pipeline accidents would provide a basis to carry out consistent statistical analyses and reduce errors in risk evaluation modelling. For example, the categories of the receiving environment are very basic in the PHMSA database including only HCAs, soils, water, and simple categories of wildlife. Moreover, environmental consequences are only reported in a binary yes/no fashion. This makes it impossible to statistically evaluate the severity of the environmental impact and to determine how to effectively improve response plans, making them both cost-effective and protective of the most commonly affected or most sensitive

environmental receptors. Including more information about the receiving environment in historical databases would improve risk analysis by incorporating mathematical/quantitative approaches (i.e. simulations based on historical data) to the more often adopted qualitative methods (i.e. risk rating scales). The union of qualitative and quantitative analysis would help risk analysts and decision makers to better assess environmental risks associated with hazardous liquid pipeline accidents.

Declarations

Author contribution statement

Chiara Belvederesi, Megan S. Thompson, Petr E. Komers: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

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